Physically Based Estimation of Bare-Surface Soil Moisture With the Passive Radiometers

Jiancheng Shi, *Senior Member, IEEE*, Lingmei Jiang, Lixin Zhang, K. S. Chen, *Senior Member, IEEE*, Jean-Pierre Wigneron, *Senior Member, IEEE*, André Chanzy, and Thomas J. Jackson, *Fellow, IEEE*

***Abstract*—A physically based bare-surface soil moisture inversion technique for application with passive microwave satellite measurements, including the Advanced Microwave-Scanning Radiometer—Earth Observing System, Special Sensor Microwave/Imager, Scanning Multichannel Microwave Radiometer, and Tropical Rainfall Measuring Mission Microwave Imager, was developed in this paper. The inversion technique is based on the concept of a simple parameterized surface emission model, the Q_p model, which was developed using advanced integral equation model simulations of microwave emission. Through evaluation of the relationship between roughness parameters Q_p at different polarizations, it was found that they could be described by a linear function. Using this relationship and the surface emissivities measured from two polarizations, the effect of the surface roughness is cancelled out. In other words, this approach consisted in adding different weights on the v and h polarization measurements so as to minimize the surface roughness effects. This method leads to a dual-polarization inversion technique for the estimation of the surface dielectric properties directly from the emissivity measurements. For validation, we compared the soil moisture estimates, derived from ground radiometer measurements at C- to Ka-band obtained from the Institute National de Recherches Agronomiques' field experimental data in 1993 and the Beltsville Agricultural Research Center's field experimental data at C- and X-band obtained in 1979–1982, with the field *in situ* soil moisture measurements. The accuracies [root-mean-square error (rmse)] are higher than 4% for the available experimental data at the incidence angles of 50° and 60°. The newly developed inversion technique should be very useful in monitoring global soil moisture properties using the currently available satellite instruments that commonly have incidence angles between 50° and 55°.**

***Index Terms*—Inversion technique, passive microwave, roughness, soil moisture.**

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J. Shi is with the State Key Laboratory of Remote Sensing Science, jointly sponsored by the Institute of Remote Sensing Applications, Chinese Academy of Sciences, and by Beijing Normal University, Beijing, China, and also with the Institute for Computational Earth System Sciences, University of California, Santa Barbara, CA 93106 USA (e-mail: shi@icess.ucsb.edu).

L. Jiang and L. Zhang are with the Center of Remote Sensing and Geographical Information Systems, Beijing Normal University, Beijing 100871, China.

K. S. Chen is with the Center for Space and Remote Sensing Research, National Central University, Chung-Li 32054, Taiwan, R.O.C.

J.-P. Wigneron is with Institute National de Recherches Agronomiques (INRA) Ecologie fonctionnelle et Physique de l'Environnement (EPHYSE), 33883 Bordeaux, France.

A. Chanzy is with the Institute National de Recherches Agronomiques (INRA), 84000 Avignon, France.

T. J. Jackson is with the Hydrology and Remote Sensing Laboratory, United States Department of Agriculture—Agricultural Research Service (USDA—ARS), Beltsville, MD 20705 USA.

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TABLE I
SENSORS CONSIDERED IN THIS STUDY AND THEIR PARAMETERS

Instrument	Incidence in degree	Frequency in GHz	Polarization	Resolution in km
SSM/I	53.1	18.35, 22.235*, 37.0, 85.5	v, h	15-70
SSMR	50.3	6.6, 10.7, 18, 21, 37	v, h	30-150
AMSR-E	55	6.925, 10.65, 18.7, 23.8, 36.5, 89	v, h	6-75
TMI	52.8	10.65, 19.35, 21.3*, 37 , 85.5	v, h	6-50

Note: * for v polarization only

I. INTRODUCTION

SOIL MOISTURE plays an important role in the interactions between the land surface and the atmosphere, as well as the partitioning of precipitation into runoff and ground water storage. Studies using general circulation models (GCMs), incorporating land-surface parameterization, have shown that strong feedback exists between the soil moisture anomalies and climate [1]. Global soil moisture observations could prove to be very useful in hydrology, meteorology, climatology, and agriculture.

Microwave remote sensing provides a feasible satellite-based technique for mapping spatially distributed soil moisture. Investigations have established the fundamentals of a passive-microwave remote sensing for monitoring the temporal and spatial variations of regional soil moisture [2]–[9]. Currently, there are several passive-microwave satellites available including the Advanced Microwave Scanning Radiometer—Earth Observing System (EOS) (AMSR—E) onboard NASA's EOS Aqua Satellite, the Special Sensor Microwave/Imager (SSM/I) on the Defense Meteorological Satellite Program (DMSP), the Scanning Multichannel Microwave Radiometer (SSMR) on the Nimbus-7 Satellite, and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) onboard the TRMM satellite. All of these provide the brightness temperature measurements using a conical scan with an incidence angle of 50°–55° for multiple frequencies and polarizations. The sensor parameters for these instruments are summarized in Table I.

The application of microwave-based retrieval of soil moisture to hydrological and meteorological sciences has been influenced or limited to a certain degree by the natural variability and complexity of the vegetation canopy and surface roughness that significantly affect the sensitivity of the emission measurements to soil moisture. There are several techniques available for the estimation of surface soil moisture from the passive microwave measurements.

1) Single-channel algorithm—h-polarized brightness temperature is corrected sequentially for surface temperature, vegetation water content, and surface roughness using ancillary data, to obtain the equivalent emissivity for bare smooth soil [2], [3], and is then used with a dielectric model to obtain the soil moisture.
2) Multifrequency-polarization iterative algorithm—The soil moisture estimates are adjusted iteratively in computations of brightness temperature measurements TBv and TBh with a radiative transfer model—the $\omega - \tau$ model—and compared with measurements from 6.9–18 GHz or from 10–18 GHz (depending on the radio-frequency interference conditions) until the difference between the computed and observed brightness temperatures is minimized in a least squares sense. This approach is currently used for AMSR retrievals to derive the surface soil moisture and vegetation water content [5], [6] or a combined surface roughness and vegetation parameter [7].
3) Polarization-index algorithm—In this approach, soil moisture is linearly related to brightness temperature measurements at 6.9 GHz and uses the normalized brightness temperature (polarization index) at 10 GHz to correct the vegetation effects on the intercept and slope of the linear relationships at 6.9 GHz [8].

In all of these techniques, the surface emission component or effective reflectivity R_p^{e} is commonly described by a semi-empirical model—the Q/H model [9], [10]. It is directly related to soil moisture information and is given as [9], [10]

$$R_p^{\mathrm{e}} = 1 - \varepsilon_p = [Q \cdot r_q + (1 - Q) \cdot r_p] \cdot H. \tag{1}$$

Equation (1) describes the bare-surface effective reflectivity as a function of the surface roughness and dielectric properties. r_p is the Fresnel reflectivity at polarization p. The surface roughness parameters Q and H in (1) are assigned values between zero and one to account for the surface roughness effect on reflectivity. The parameter Q describes the energy emitted in the orthogonal polarization (between v and h) due to the surface roughness effect. H describes the effect of surface roughness, resulting in a decrease in the effective reflectivity. However, it has been recognized for some time that there is a difference between direct ground surface roughness measurements and those derived by fitting the Q/H model using ground soil moisture or dielectric-constant measurements [11]. They are usually determined empirically from experimental data for a given frequency and incidence angle, and are often called "effective roughness." Since the Q/H model utilizes three parameters—the surface dielectric constant and two roughness parameters Q and H—it is difficult to perform a direct inversion with only dual-polarization measurements at a given frequency since it is not possible to separate the effects of the surface roughness and dielectric properties. In the single-polarization inversion technique described in [2]–[4], the Q/H model is modified by assuming $Q = 0$. The surface roughness correction factor H for h polarization measurement must be determined from other data sources in order to estimate soil moisture. Retrieval methods utilizing dual-polarization measurements generally assume that $Q = 0$ with the different description forms of H functions. They differ in the dependence or sensitivity to surface roughness properties [12]–[15]. However, this type of model usually employs an extremely poor description of the relationship between the emission signals of the different polarization and might not be suitable for application in the high-frequency and large incident dual-polarization measurements, as demonstrated in [16].

A simple surface emission model, called the Q_p model, has been developed recently [16]. This model is specifically suitable for applications with high-frequency and large incidence angle radiometer measurements from AMSR—E, SSM/I, SSMR, and TMI. It was developed using the advanced integral equation model (AIEM)-simulated [17] database for a wide range of the surface soil moisture and roughness properties, and has a very simple form for the effective reflectivity

$$R_p^{\mathrm{e}} = Q_p \cdot r_q + (1 - Q_p) \cdot r_p \tag{2.1}$$

and for emissivity

$$\varepsilon_p = Q_p \cdot t_q + (1 - Q_p) \cdot t_p \tag{2.2}$$

where r_p and t_p are the Fresnel reflectivity and transmittivity with $r_p = 1 - t_p$. Q_p is the surface roughness parameter, with the dependence on polarization p and the surface roughness properties. This model can also be considered as a modification of the Q/H model, with $H = 1$, and the Q_p parameters defined by a polarization dependence that provides a correction of the effects of surface roughness at different polarizations in comparison with the Q/H model. In the Q_p model, the roughness parameters Q_p work in both forms of the effective reflectivity, as in (2.1), and emissivity, as in (2.2). They are proportional and positively related to a single surface roughness property: s/l—the ratio of rms height to the correlation length. Physically, Q_p describes the magnitude of the exchange in the emitted energies between the orthogonal polarizations (v and h) due to the surface roughness effect. It indicates that the rougher surface (larger s/l) will result in more depolarization than a smoother surface. They can be well described by a nonlinear form. At 10.65 GHz and 55° for AMSR—E, the Q_p functions, as shown in [16], are

$$\log[Q_v] = 3.2165 + 2.4528 \cdot \log(s/l) - 6.6741 \cdot (s/l) \tag{3.1}$$

$$\log[Q_h] = 5.6036 + 3.0950 \cdot \log(s/l) - 9.3776 \cdot (s/l). \tag{3.2}$$

The relationships between the Q_p parameters at 10.65 GHz and the other frequencies are also given in [16]. The root-mean-square errors (rmses) for predicting the effective reflectivity R_v^{e} and R_h^{e} are all extremely small—around 0.002. Shi *et al.* [16] demonstrated that the Q_p model is very simple, accurate, and suitable for microwave remote-sensing applications, with a negligible error in comparison with the AIEM model simulations.

The objective of the present study is to develop a bare-surface soil moisture inversion model for the currently available passive microwave satellite instruments, including AMSR—E, SSM/I, SSMR, and TMI. As our focus is on soil moisture applications, the sensor frequencies considered were limited to C-band and to Ka-band at 6.925, 10.65, 18.7, and 36.5 GHz. In addition, the effects of soil temperature and the moisture distribution along the soil vertical profile are not considered in this study.

We will first describe the algorithm development methodology under the Q_p model's concept, the evaluations using the AIEM-simulated database under the AMSR—E sensor configuration at 55°, its extension to the other sensor configurations, and the error sensitivity test. Following this, the algorithm performance is evaluated using two experimental ground radiometer measurements from the C- to Ka-band obtained in 1993 [14], [15] and from the C- and X-band obtained in 1979 and 1981 [18], [19].

II. Inversion Algorithm Development Using AIEM-Simulated Database

A. Basic Considerations

For bare soils, dual-polarization measurements at a given frequency from currently available satellites provide an opportunity to minimize the surface roughness effects and to estimate soil moisture, directly under the assumption that the physical temperature of soil is known. When the soil properties, including temperature and moisture, have no significant variation along its vertical profile, the surface emission signals are described as a function of surface dielectric and roughness properties. For a bare flat surface, the effects of the surface dielectric properties on emission can be evaluated through the Fresnel reflectivity. The Fresnel reflectivities are well correlated at different polarizations (v and h) and at different frequencies, for half-space dielectric media. For the natural surfaces, the surface emissivity is affected by both the surface dielectric and roughness properties. Estimation of natural surface soil moisture is commonly obtained by the estimation of the Fresnel reflectivity, by correcting for the effect of surface roughness. When compared to the currently available semi-empirical surface emission models, with the Q_p model, it is much easier to separate the effect of surface roughness from the dielectric properties than with the Q/H model. This makes it possible to reduce the effect of surface roughness and to estimate the surface dielectric properties, by directly using dual-polarization measurements. Both the surface roughness parameters Q_v and Q_h can be described as functions of the surface roughness property s/l [(3.1) and (3.2)]; therefore, there are only two unknowns—surface dielectric and roughness parameter s/l in the Q_p model described by (2.1) and (2.2), if the surface physical temperature is available. In theory, these could be estimated using dual-polarization measurements at a given frequency with the Q_p model in (2.1) (2.2), (3.1), and (3.2). The solution involves a numerical technique to solve the two nonlinear equations for the two unknowns. The problems that occur in using this technique include possible multiple solutions and intensive computation. As a result, there can be significant uncertainties in the estimation of soil moisture, and the results may not be suitable for image-based global-data analyses when dealing with the large data volume. Therefore, there is a need to develop a simple and accurate inversion algorithm that could be easily applied to image-based global soil moisture monitoring.

In order to develop the simple inversion algorithm, it is necessary to evaluate if there is a good direct relationship between surface roughness parameters Q_p for the different polarizations v and h. If such a relationship exists and can be described with a simple form, then the surface roughness parameters in the Q_p model can be considered as a single unknown in the inversion processes. Thus, it reduces the dimensionality of the problem and the complexity in the inversion process.

B. Bare-Surface Algorithm Development

In order to evaluate and characterize the effects of roughness and to develop the algorithm, we generated a surface emission database using the AIEM model [17] for the following AMSR—E sensor parameters: frequencies of 6.925, 10.65, 18.7, and 36.5 GHz, both v and h polarizations, and 55° incidence angle. This database covers a wide range of surface dielectric constants that are calculated from the corresponding volumetric soil moisture (2%–44% at 2% interval) by Dobson's dielectric mixing model [20], with a given soil texture property and surface roughness parameters (rms height from 0.25–3 cm at a 0.25-cm interval and the correlation length from 2.5–30 cm at a 2.5-cm interval). There were 2904 simulated emissivities for each frequency and polarization. The commonly used Gaussian correlation function was used in the simulation since it is a better approximation for high-frequency microwave measurements than an exponential correlation function [16]. These simulated surface emission signals will be used to demonstrate the principle and techniques of our algorithm development.

Using the simulated database, we first obtained the surface roughness parameters Q_v and Q_h in (2.1) and (2.2) for a wide range of surface roughness and dielectric properties. Fig. 1 shows the relationships between the roughness parameters Q_h (x axis) and Q_v (y axis) from the AIEM-simulated data of AMSR—E for 6.925, 10.65, 18.7, and 36.5 GHz at 55°. It can be seen that the relationship between Q_v and Q_h is highly correlated at a given frequency and that the relationship between these two terms can be approximately described as a linear function

$$Q_v(f) = a(f) + b(f) \cdot Q_h(f). \tag{4}$$

The regression coefficients a and b are determined for each frequency using the surface roughness parameters Q_v and Q_h obtained from the AIEM model [17] simulated database for the AMSR—E sensor configuration. The solid line in each plot in Fig. 1 represents the linear relationship of (4). It can be seen that the errors are extremely small. Therefore, with the relationship (4), one surface roughness parameter can be predicted from the other, reducing roughness to a single unknown.

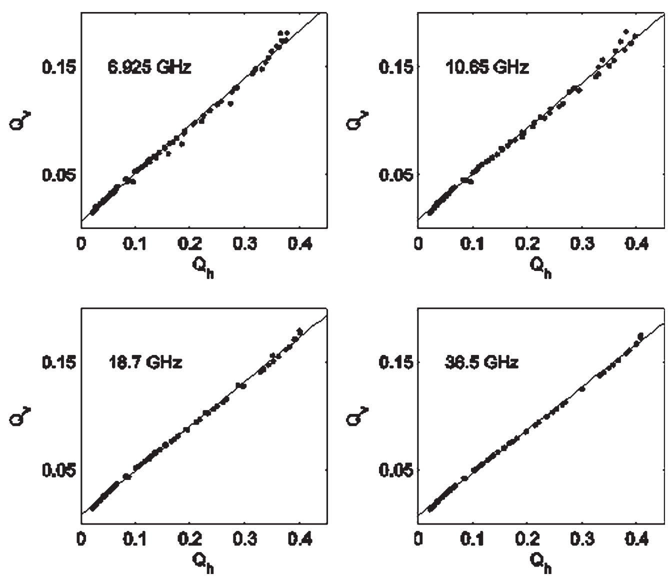

Fig. 1. Relationships between the roughness parameters Q_h (x axis) and Q_v (y axis) from the AIEM-simulated data for the AMSR—E at 6.925, 10.65, 18.7 and 36.5 GHz, with the solid line presented by the linear function of (4).

By rearranging the Q_p model (2.2) and inserting it into (4), and then combining the coefficients, the inversion algorithm can be derived

$$\alpha \cdot \varepsilon_v + \varepsilon_h = \beta \cdot t_v + \eta \cdot t_h. \tag{5}$$

It can be shown that the relationships of the coefficients between (4) and (5) are $\alpha = 1/b$, $\beta = (1-a)/b$, and $\eta = (1+a)/b$. With a known surface physical temperature, the surface effective emissivity ε_p on the left side of (5) can be obtained from the brightness temperature measurements. The t_p on the right side of (5) is the Fresnel transmittivity, which depends only on the surface dielectric properties and the incidence angle. The algorithm presented in (5) results in the canceling out the effect of the surface roughness and provides a direct estimate of the surface dielectric constant through its relationship to the weighted sum of t_p at a given frequency. The coefficients α, β, and η at each frequency are given in Table II for the AMSR—E instrument. As it can be noticed, the algorithm (5) is in a form of the weighted sum of the emissivities—$\alpha \cdot \varepsilon_v + \varepsilon_h$ rather than the forms of ratio or difference. This is because the effect of roughness on the effective reflectivity or emission at a large incident angle differs in both the magnitude and direction (referring to an increase or decrease of the effective reflectivity) at the two different polarizations [16]. The effect of the surface roughness increases the emission signal at h polarization but decreases the emission signal at v polarization, in comparison with that from a flat surface. As the result, the adding of two polarization emission signals will actually reduce the roughness effects. The weighted sum of the emissivities on the left side of (5) actually makes the decreased emission signal in v polarization equal to that increased emission signal in h polarization due to the surface roughness effects in comparison with the flat surface. It leads to the cancellation of the surface roughness effects and to the weighted sum of the Fresnel transmittivity $\beta \cdot t_v + \eta \cdot t_h$ on the right side of (5). This is why the corresponding coefficients at each polarization are almost equal. That is, the coefficient β is very close or similar to α, and the coefficient η is very close to one at all frequencies, as shown in Table II. Following the same procedures as described above, these coefficients for the other sensors considered in this study can be also derived and listed in Table II. They are dependent only slightly on the frequency. This is because the frequency dependence of the roughness parameters Q_p is quite small. As shown in [16], Q_v decreases very slightly, while Q_h increases as the frequency increases. This characteristic of the frequency dependence of the surface roughness parameter agrees well with the geometric optical model that predicts that the bistatic scattering coefficient has no frequency dependence.

Furthermore, the relationship between the soil moisture (SM) and the weighted sum of the Fresnel transmittivity on the right side of (5) can be derived using a second-order regression relationship

$$\mathrm{SM} = A + B \cdot (\beta \cdot t_v + \eta \cdot t_h) + C \cdot \sqrt{\beta \cdot t_v + \eta \cdot t_h}. \tag{6}$$

The coefficients A, B, and C can be determined by a regression analysis between a range of the soil moisture, 2%–50% at 2% interval, and the right side of (5), calculated by the surface dielectric constants using Dobson's dielectric mixing model [20], with given soil texture data for the corresponding soil moisture. They differ at the different frequencies, incidence angles, and soil texture properties. This relationship gives an accuracy of calculating soil moisture higher than 0.1%. The SM estimates can be done by replacing $\beta \cdot t_v + \eta \cdot t_h$ in (6) with $\alpha \cdot \varepsilon_v + \varepsilon_h$. Thus, the surface soil moisture can be estimated by using dual-polarization v and h measurements at a given frequency.

Fig. 2 shows the histogram of the absolute estimation error for volumetric soil moisture, in percent, at 10.65 GHz. It was produced by the differences between the input soil moisture that were used to generate the surface emission database and that were retrieved from the corresponding simulated emissivity using (5) and (6). The inversion accuracy in terms of the rmse in estimating volumetric soil moisture is 0.28%, with the maximum absolute error of 0.92%. The errors at the other frequencies are also remarkably small with rmses of 0.28%, 0.33%, and 0.44% for 6.925, 18.7, and 36.5 GHz, respectively. These results indicate that the surface roughness effects in the AIEM-simulated emission signals can be minimized with dual-polarization measurements at each frequency.

C. Sensitivity Test

In order to evaluate the behavior of the inversion model (5) for estimating soil moisture with potential sources of error, we performed sensitivity tests by introducing both absolute and relative errors to the AIEM-simulated data. This was done by adding or subtracting an error simultaneously to both the V and H polarizations of the AIEM-simulated data for the evaluation of the effects of the absolute error (difference with the AIEM-simulated emission data). The relative error was introduced in the AIEM-simulated emission data by a plus or minus error

TABLE II
BARE-SURFACE INVERSION MODEL PARAMETERS IN (5)

AMSR-E (55°) Frequency in GHz	6.925	10.65	18.7	36.5	TMI(52.8°) Frequency in GHz	10.65	19.35	37
α	2.2341	2.3251	2.3962	2.4699	α	2.494	2.441	2.418
β	2.1971	2.2856	2.3544	2.4262	β	2.487	2.423	2.392
η	1.0519	1.0533	1.0549	1.0566	η	0.998	1.016	1.031
SSMR (50.3°) Frequency in GHz	6.6	10.7	18	37	SSM/I (53.1°) Frequency in GHz		18.35	37
α	2.5329	2.4322	2.3818	2.3719	α		2.4268	2.4686
β	2.4905	2.3840	2.3302	2.3194	β		2.3802	2.4182
η	1.0463	1.0542	1.0590	1.0603	η		1.0569	1.0612

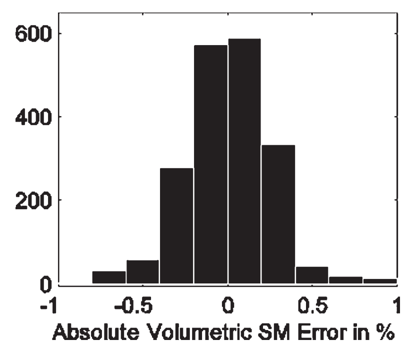

Fig. 2. Histogram of the absolute error for the estimation of volumetric soil moisture, in percent, from the AIEM-simulated data at the frequency of 10.65 GHz and 55° incidence angle.

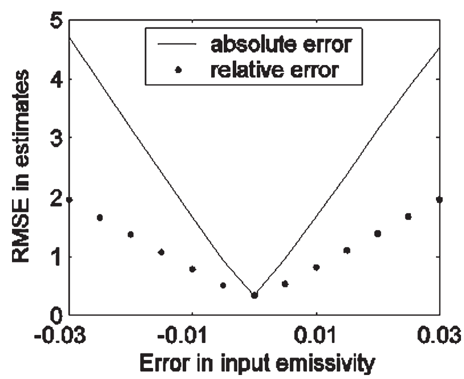

Fig. 3. RMSE of volumetric soil moisture estimation, in percent, by the inversion model (5) at 10.65 GHz, as a function of the absolute error (solid line) and relative error (dotted line).

to one polarization and with an opposite sign to the other polarization. The errors represent the differences between the AIEM-simulated data and the measurements, including errors due to model prediction, instrument calibration, and other measurement errors. Fig. 3 shows the rmse of the volumetric soil moisture estimation, in percent, using the inversion model (5) and (6) at 10.65 GHz, as a function of the absolute (solid line) and relative errors (dotted line). It can be seen that the algorithm is more sensitive to the absolute errors than the relative error. This is because the inversion is based on the weighted sum of the emissivities from both polarizations, as described by (5). The absolute error, introduced by a plus or minus error in both polarizations simultaneously, will be $(\alpha + 1)$ of the error's magnitude [where α is the coefficient used in (5) and given in Table II] and has more impact on the soil moisture estimation. The relative error, introduced by adding the error's magnitude to one polarization and subtracting it from the other polarization, has less impact, since the actual error introduced is only at $(\alpha - 1)$ of the error's magnitude. Both the absolute and relative errors result in a biased estimation of soil moisture.

III. VALIDATION WITH FIELD EXPERIMENTAL DATA

Two sets of field experiment data were used to validate the algorithm developed in this study. The first data set is described in [14] and [15] and consists of microwave radiometer measurements obtained from a crane-mounted multifrequency microwave radiometer at frequencies of 5.05, 10.65, 23.8, and 36.5 GHz, and an incidence of 50° over the 18 × 40 m experimental fields at the remote-sensing test site of the Institute National de Recherches Agronomiques (INRA), Avignon, France. This data set was acquired during the period of April 20 to July 10, 1993, over six bare fields with a very large range of surface roughness conditions. The ground surface roughness profile measurements, which are available from three to six profiles for each bare field, showed that the rms height ranged from 0.2–7.1 cm, and the ratio of the rms height to the correlation length ranged from 0.01–0.78. The surface emissivities ε_v and ε_h for each frequency polarization were derived by using the brightness temperature measurements, the estimated sky temperature, and the mean surface physical temperature at 2 cm [15]. Due to the frequencies used, we assumed that the deep soil effect was not significant. During the experiment, a large range of soil moisture conditions, 2%–46% by volume, was obtained by irrigating the fields and then letting them dry out. The average ground soil moisture measurements within the field and the 2-cm depth were used. Additional details on this data set can be found in [14] and [15].

Since there are some slight differences between the sensor parameters listed in Table I and those of this instrument, in terms of frequencies and incidence angles, we simulated an emissivity database for the field experiment instrument frequencies at a 50° incidence using the AIEM model. The coefficients of α, β, and η in (5) were determined following the same procedure described in the last section. They are quite similar to the SSMRs coefficients listed in Table II at 10.65 and 36.5 GHz, and differ only slightly at 5.05 GHz, since the C-band SSMR coefficients were determined at 6.6 GHz. For the estimation of SM, we used as input the estimated emissivity into the left side of (5) $\alpha \cdot \varepsilon_v + \varepsilon_h$ and then converted it into the soil moisture using (6), with the coefficients A, B, and C determined by the

TABLE III
SUMMARY OF THE TEST RESULTS (rmse) ON THE ESTIMATION OF SOIL MOISTURE USING (5), (7.1), AND (7.2) FROM INRA DATA

Frequency in GHz / method	5.05	10.65	23.8	36.5
Regression h with individual field (7.1)	2.9 %	2.4 %	2.9 %	3.2 %
Algorithm (5)	4.1 %	3.8 %	3.5 %	3.8 %
Regression h with all fields (7.2)	5.3 %	5.6 %	6.0 %	5.9 %

field soil texture data at each experimental frequency at 50° incidence angle.

In addition to evaluating the algorithm described by (5), we also performed two tasks with two simple empirical approaches, using the linear functional form with the coefficients determined by the experimental data emissivities and the ground soil moisture measured for h polarization at each frequency. The first task is to evaluate a roughly possible "noise" level in the experimental data on the estimation of the soil moisture

$$\mathrm{SM} = e(f, i) + g(f, i) \cdot \varepsilon_h(f, i). \tag{7.1}$$

This was done by performing the regression for (7.1) with each field's soil moisture and emissivity at each frequency. In other words, the coefficients e and g in (7.1) were determined at each individual test field i and at each frequency f. Under the assumption that the soil moisture is linearly related to the emissivity, this task provides the errors resulting from the uncertainties that include the estimated emissivities from the radiometer measurements, the ground soil moisture measurements that were used as the "ground truth," the roughness change during the experiment, the radiometer's footprint registration error, and the nonlinear approximation of (7.1). It closely represents what the best one can do in estimating soil moisture from this experimental data set. Therefore, the errors from this task may be considered as a roughly possible "noise" level of this experimental data set. The soil moisture rmses of the first regression task from the individual test field are 2.9%, 2.4%, 2.9%, and 3.2% for 5.05, 10.65, 23.8, and 36.5 GHz, respectively.

For the second task

$$\mathrm{SM} = e(f) + g(f) \cdot \varepsilon_h(f) \tag{7.2}$$

the regression was carried out using all the available data from the six test fields to determine the coefficients e and g in (7.2), for each frequency f. This task evaluated whether the two different approaches to estimation, (5) and (7.2), were significantly different. If there is no significant difference, there would be no value in applying (5), because the roughness effect may be under the measurement "noise" level. The rmse on the estimations of the absolute volumetric soil moisture, in percent, from each method and frequency are summarized in Table III.

Fig. 4 compares the ground-measured volumetric soil moisture measurements (x axis), 2-cm vertical depth, with the algorithm (5) (top row) and the regression task (7.2) (bottom row) using all the available data at each frequency. The plots from left to right are for the different frequencies, 5.05, 10.65, 23.8, and 36.5 GHz. It can be seen that the algorithm (5) works much better than that from the regression approach (7.2). The inversion accuracies (rmse) in estimating the volumetric soil moisture of (5) 4.1%, 3.8%, 3.5%, and 3.8% for 5.05, 10.65, 23.8, and 36.5 GHz, respectively. These accuracies for each frequency are only slightly worse than the possible "noise" level from the first regression test, as shown in the top row of Table III. The difference ranges from 0.6% to 1.4%. On the other hand, the corresponding inversion accuracies from the regression approach (7.2) are 5.3%, 5.6%, 6.0%, and 5.9%. Since the coefficients were determined directly from all the test data using (7.2), the results represent the correction of the averaged roughness effect over all the measured fields. Therefore, the roughness effects have been partially reduced. For the smoother and rougher fields, the surface roughness effects were, respectively, overcorrected or undercorrected when using (7.2). In comparison with the results from (5), the improvements range from 1.2% to 2.5% for the different frequencies. Note that both methods (7.1) and (7.2) were calibrated from the experimental data set, while the method given by (5) was derived from the AEIM simulations, independently, of the measured data. Thus, these results indicate that our newly developed algorithm (5) can significantly minimize the surface roughness effect and improve soil moisture estimation.

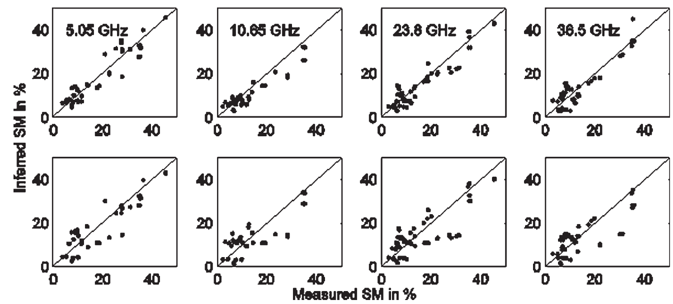

Fig. 4. Comparisons of the ground volumetric soil moisture measurements (x axis), 2-cm vertical depth, with that inferred (y axis) from the INRA measurements at each frequency. The top and bottom rows are from using the inversion model (5) and the regression (7.2), with all the available data. The plots from left to right are for 5.05, 10.65, 23.8, and 36.5 GHz, respectively.

The second experimental data set used for the algorithm evaluation is a truck-mounted microwave radiometer data set consisting of C-band (5.0 GHz) and X-band (10.65 GHz) observations made over several bare-surface test sites at Beltsville, MD, during a two-year period in 1979 and 1981 [18], [19]. The ground-based radiometer used in the experiment was a dual-polarized Dicke radiometer that measured the microwave brightness temperature for both vertical and horizontal polarizations, almost simultaneously. The reported calibration accuracy is about ±3 K. Soil moisture and temperature ground truth, as well as the soil bulk density and texture, were acquired simultaneously with the microwave radiometer measurements. These experimental data have been used to study the effects of the soil texture, surface roughness, and vegetation cover on the remote sensing of soil moisture content by microwave radiometers and are well documented in [18] and [19].

The measured surface temperatures were used to derive emissivities from the brightness temperature observations. The same coefficients in (5), for the INRA 5.05- and 10.65-GHz data

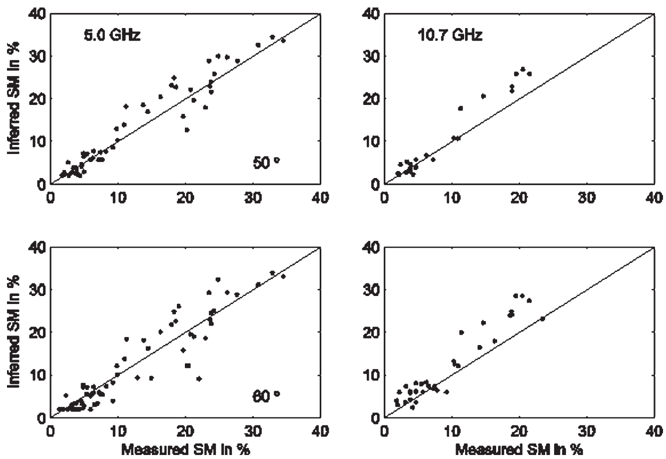

Fig. 5. Comparisons of the ground-based volumetric-soil moisture measurements (x axis) with that inferred (y axis) by using the dual-polarization brightness temperature measurements at each frequency from BARC. The plots are for the two frequencies with the C-band at (left) 5.0 GHz and the X-band at (right) 10.7 GHz, and the two incidence angles at (top) 50° and (bottom) 60°.

incidence, were used for the Beltsville Agricultural Research Center (BARC) 5.0- and 10.7-GHz data at 50°, since there is very little difference in the frequency. The coefficients for (5) at 60° were determined from the simulated emissivity database. Fig. 5 shows the comparisons of the ground volumetric soil moisture measurements (x axis), 2.5-cm vertical depth, with those inferred (y axis), by using the dual-polarization brightness temperature measurements at each frequency from the BARC experimental data. The plots are for the two frequencies with C-band 5.0 GHz (left) and X-band 10.7 GHz (right), and the two incidence angles at 50° (top) and 60° (bottom). It can be seen that the algorithm works also quite well. The inversion accuracies, in terms of the rmse, in estimating the volumetric soil moisture are 2.8% and 3.7% at 50° for 5.0 and 10.7 GHz, respectively. At 60°, they are 3.6% and 3.8% for 5.0 and 10.7 GHz, respectively.

IV. Conclusion

Based on a parameterized surface emission model (the Q_p model [16]), an inversion model was developed in this study. It uses dual-polarization measurements to minimize surface roughness effects and to estimate surface dielectric properties directly. This was done by evaluating the relationship between the surface roughness parameters Q_v and Q_h at different polarizations. It was found that the relationship between Q_v and Q_h can be described by a linear function. With this relationship, the inversion model can be derived. The retrieval model has a very simple form and avoids using the numerical technique by the least-square fitting in the inversion process that commonly results in a multisolution problem and is computationally intensive. For the AIEM model simulated data, the algorithm (5) has an accuracy higher than 0.5% for surface volumetric soil moisture estimation under the AMSR—E sensor configuration at 55° incidence and frequencies 6.925, 10.65, 18.7, and 36.5 GHz. The accuracy slightly decreases as the frequency increases. The best accuracy, 0.28%, can be seen at 6.925 and 10.65 GHz. The worst accuracy is 0.44% at 36.5 GHz. A similar level of accuracy is expected for the other sensors, as listed in Table I, for the AIEM-simulated surface emission data. This inversion technique uses different weights on the surface emission measurements at the different polarizations so as to minimize surface roughness effects. In this way, the weighted sum of the Fresnel transmittivities in the different polarizations can be estimated, which can be further converted to soil moisture with soil-texture information. The algorithm's weight coefficients for the flat Earth surface (no topography consideration) and for the sensors and frequencies considered in this study are given in Table II.

We performed a validation of this inversion technique using two sets of ground-based microwave radiometer experiment data, INRA with an incident angle of 50° and four frequencies (5.05, 10.65, 23.8, and 36.5 GHz) and BARC with two incident angles of 50° and 60° and two frequencies (5.0 and 10.7 GHz). These two sets have similar frequencies and cover the incidence angle range of the satellite sensors in Table I. The results indicated that the algorithm (5) worked well. The rmse, in terms of estimating the volumetric soil moisture at each frequency, and the incidence angle from both experimental data sets are all below 4%, except the INRA 5.05-GHz data at 50°, with 4.1%. In addition, we also applied a direct linear-regression estimation using the INRA93's experimental data at h polarization. This regression resulted in rmse values of 5.3%–6%. This approach had a much larger estimation error than the simple inversion technique, even though its coefficients were directly determined from the same experimental data. These results indicate that the newly developed inversion technique offers a significant improvement for minimizing the effect of surface roughness for soil moisture estimation. It should be very useful in monitoring land-surface soil moisture with the currently available passive microwave sensors.

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Jiancheng Shi (SM'02) received the B.A. degree from the University of Lanzhou, Lanzhou, China, in 1982, and the M.A. and Ph.D. degrees in geography from the University of California, Santa Barbara (UCSB), Santa Barbara, in 1987 and 1991, respectively.

He joined the Institute for Computational Earth System Sciences, UCSB as a Research Scientist. His research interests are microwave modeling snow and soil signatures, image processing and analysis, and inversion models for retrieving the physical parameters from remote-sensing data.

Lingmei Jiang was born in Zhejiang, China, on October 31, 1978. She received the B.S. degree in agricultural meteorology from the Nanjing Institute of Meteorology, Nanjing, China, in 2000, and the Ph.D. degree in geography from Beijing Normal University, Beijing, China, in 2005.

Her research interests include microwave remote sensing and modeling and retrieval of snow and soil properties.

Lixin Zhang received the B.A. degree from the University of Lanzhou, Lanzhou, China, in 1988, and the M.A. and Ph.D. degrees in geography from the Institute of Glaciology and Geocryology, Lanzhou, in 1991 and 2000, respectively.

He joined the Research Center for Remote Sensing and Geographical Information Systems (GIS), Beijing Normal University, Beijing, China as a Professor. His research interests are the physical properties of frozen soil and inversion algorithms or criteria for monitoring the physical parameters of soil from remote-sensing data.

K. S. Chen (S'86–M'87–SM'98) received the B.S. degree from the National Taiwan Institute of Technology, Taipei, Taiwan, Republic of China, and the M.S. and Ph.D. degrees in electrical engineering from the University of Texas, Arlington, in 1987 and 1990, respectively.

Since 1992, he has been with the faculty of the Center for Space and Remote Sensing Research, National Central University, Chung-Li, Taiwan, where he is now a Professor and Director. He has joint appointments at the Institute of Space Sciences and Institute of Communication Engineering at the same university. He has been the Editor-in-Chief of the *Journal of Photogrammetry and Remote Sensing*, since 2001, and is on the Editorial Board of the *Journal of Electromagnetic Waves and Applications* and *Transactions of the Aeronautical and Astronautical Society of the Republic of China*. He serves as a Technical Consultant at several national research agencies in the areas of satellite remote sensing, radar, and radio techniques. He has authored three book chapters, over 60 referred journal papers, and over 100 conference papers, in the areas of remote sensing and wave scattering and propagation. His research interests include microwave remote sensing, image processing and analysis for satellite and aircraft remote-sensing data, radio and microwave propagation and scattering from terrain and ocean with applications to remote sensing and wireless communications.

Dr. Chen is an Associate Editor of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING. He is a member of the Electromagnetic Academy. He was a Technical Chairman of PIERS 1999, held in Taipei, Taiwan. In 2001, he was appointed as Chairman of the Commission F, Taipei, China, of the International Union of Radio Science (URSI).

Jean-Pierre Wigneron (SM'03) received the B.S. degree in engineering from SupAéro, Ecole Nationale Supérieure de l'Aéronautique et de l'Espace (ENSAE), Toulouse, France, and the Ph.D. degree from the University of Toulouse, Toulouse, in 1993.

He is currently a Research Scientist and Head of the remote-sensing group, Institute National de Recherches Agronomiques (INRA) Ecologie fonctionnelle et Physique de l'Environnement (EPHYSE), Bordeaux, France. He developed microwave models and soil moisture retrieval approaches in the framework of the SMOS Mission. EPHYSE was selected within the Expert Support Laboratory (ESL), developing the level-2 SMOS inversion algorithm. He was a Principal and Coinvestigator of several ground and airborne international campaigns in the field of microwave remote sensing. He is a member of the Editorial Board of *Remote Sensing of the Environment*. His research interests are in microwave remote sensing of soil and vegetation, radiative transfer, and data assimilation.

André Chanzy received the Ph.D. degree in physics of the environment from the Institut National Agronomique Paris-Grignon, Paris, France, in 1991.

He has been with the Soil Science Laboratory, Institute National de Recherches Agronomiques (INRA), Avignon, France, since 1987. He currently heads the Climate Soil and Environment Laboratory. His scientific fields of interest are soil water flow modeling, the application of microwave remote sensing (active and passive), and *in situ* observations to infer hydrological fluxes.

Thomas J. Jackson (A'86–SM'96–F'02) received the Ph.D. degree in civil engineering from the University of Maryland, College Park, in 1976.

He is currently a Hydrologist with the U.S. Department of Agriculture's (USDA) Agricultural Research Service Hydrology and Remote Sensing Laboratory, Beltsville, MD. His research involves the application and development of remote-sensing technology in hydrology and agriculture. His initial research with USDA extended his Ph.D. work on the use of visible/near-infrared satellite data for deriving land-cover parameters used in hydrologic models. He has also investigated the use of an airborne laser profiler for measuring and monitoring soil erosion. The results of this research resulted in a paper "Airborne Laser Measurements of the Surface Topology of Simulated Concentrated Flow Gullies." His current research focuses on the use of passive microwave techniques in hydrology. These studies have ranged from small-scale controlled-condition field experiments, utilizing truck-mounted radiometers, to large-scale multitemporal aircraft mapping. He is the leader of a series of large-scale field experiments designed to extend high-resolution research to satellite scales. In conjunction with this, he is a Principal Investigator of studies involving SSM/I, TRMM, ADEOS-II, Aqua, Envisat, and ALOS.

Dr. Jackson received The Paper of the Year Award from the American Society of Agricultural Engineers for his paper "Airborne Laser Measurements of the Surface Topography of Simulated Concentrated Flow Gullies," in 1990, and the Prize Paper Award for his "Diurnal Observations of Surface Soil Moisture Using Passive Microwave Radiometers" at the International Geoscience and Remote Sensing Symposium in 1994. In 1999, he received the National Society of Professional Engineers 1999 Engineer of the Year Award for USDA—ARS. In 2000, his paper on aircraft mapping "Soil Moisture Mapping With Passive Microwave Imagery Data and Geostatistical Analysis" received the Remote Sensing and Hydrology 2000 Symposium Best Paper Award from the International Association of Hydrological Sciences. He is a Fellow of the American Geophysical Union and currently a member of the Administrative Committee of the IEEE Geoscience and Remote Sensing Society.